FUTURE OF ELECTRIC PROPULSION

May 20, 2019

John Brophy and Dan Goebel

Jet Propulsion Laboratory

California Institute of Technology

Outline

- Introduction
- Past
- Present
- Future

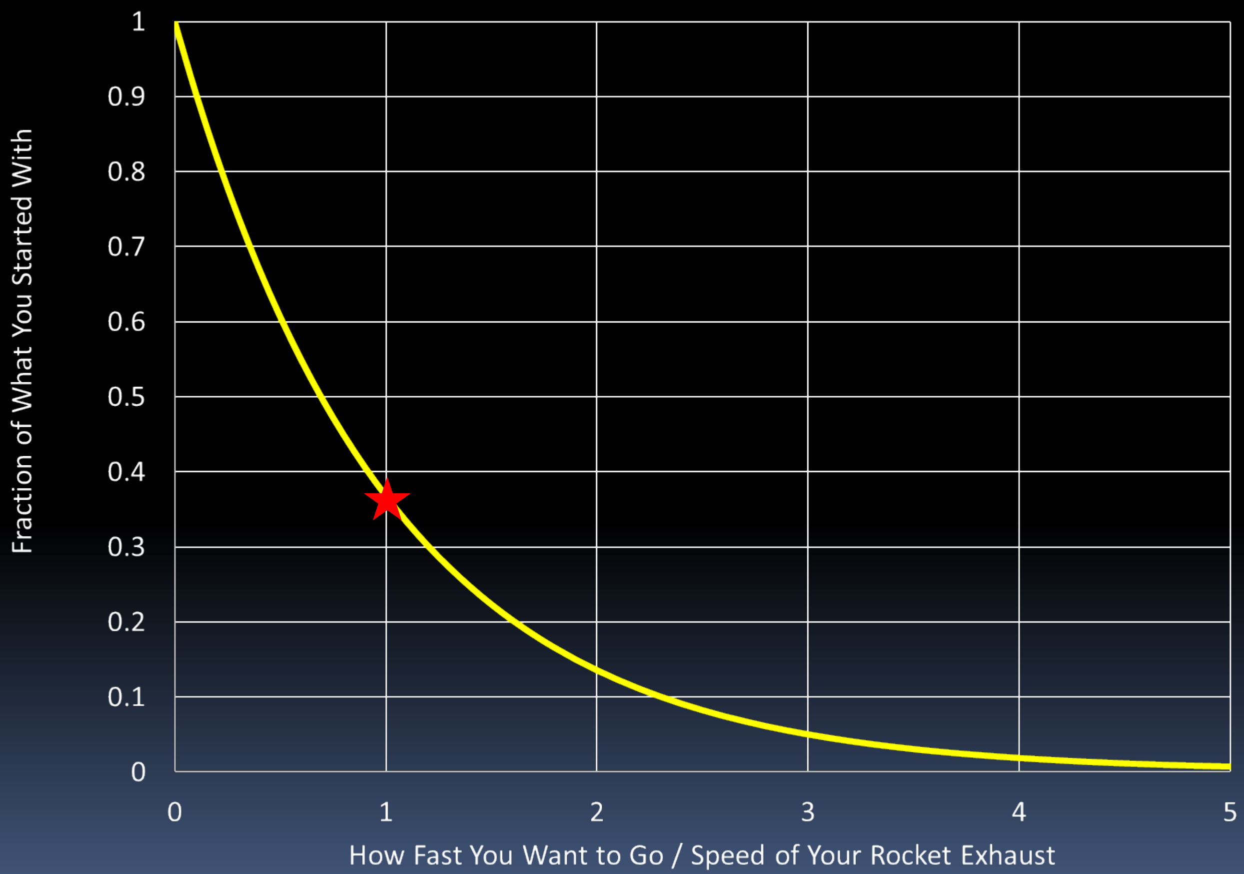
Introduction

- Why electric propulsion?
- How
- Things to be mindful of when designing an electric propulsion system

Why Electric Propulsion?

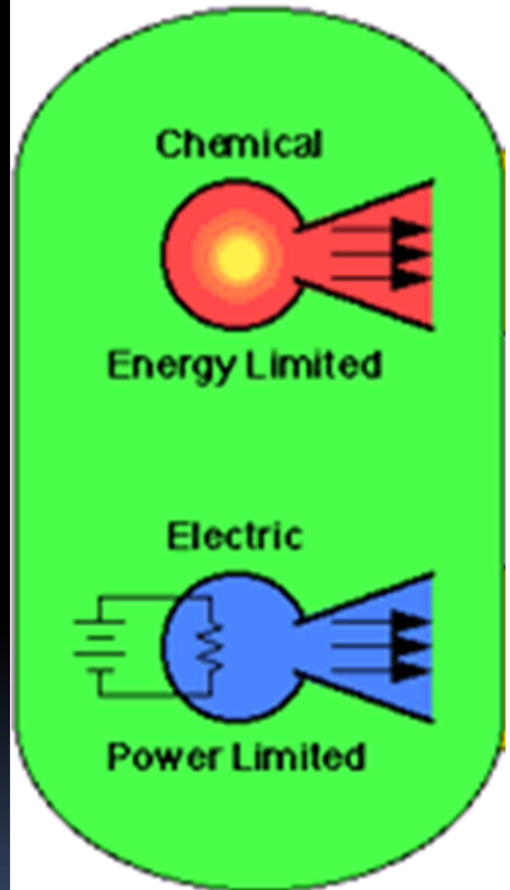
$$\frac{m_f}{m_i} = e^{-\frac{v_{s/c}}{v_{ex}}}$$

The faster you want to go, the higher your exhaust velocity must be



Decouple the Propellant from the Energy to Accelerate It

- **Chemical propulsion systems:**
  - Carry the energy for propulsion with the propellant
  - Power is determined by the propellant mass flow rate
  - Performance is limited by the energy density of the propellants
- **Electric propulsion systems:**
  - Decouple the energy for propulsion from the propellants – allows more energy to be added to each kg of propellant
  - Power is generated on-board by a separate power system
  - Performance is limited by the power generated by the power system



$$E = \frac{1}{2} m v^2 \rightarrow v = 1.41\sqrt{\frac{E}{m}}$$

$$\left.\begin{aligned} P &= \frac{1}{2}\dot{m} v^2 \\ T &= \dot{m} v \end{aligned}\right\} \quad v = \sqrt{\frac{2P}{\dot{m}}}, \quad \dot{m} = \frac{2P}{v^2}, \quad T = \frac{2P}{v}$$

Types of Electric Thrusters

- **Electrothermal** → resistively heat the propellant and expand the hot gas through a nozzle

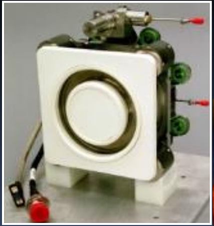
Resistojets

Arcjets

- **Electrostatic** → ionize the propellant and accelerate the ions through an electric field

Gridded Ion Thrusters

- **Electromagnetic** → ionize the propellant and accelerate the ions using crossed electric and magnetic fields

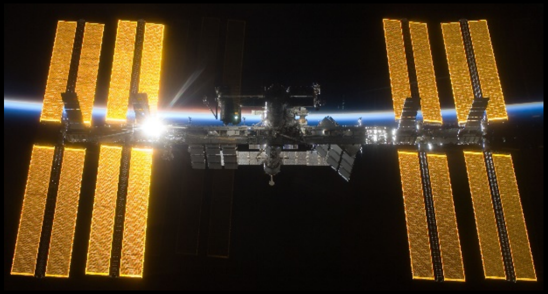


Hall Thrusters

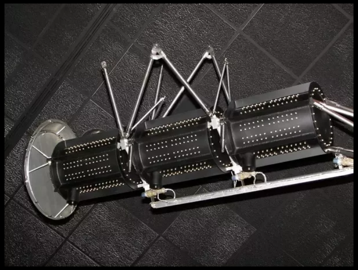
MPD Thrusters

Types of Power Sources

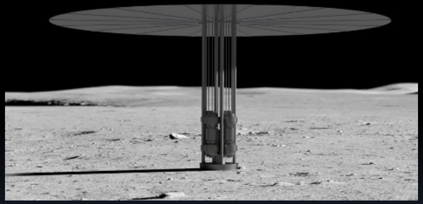
Solar Arrays



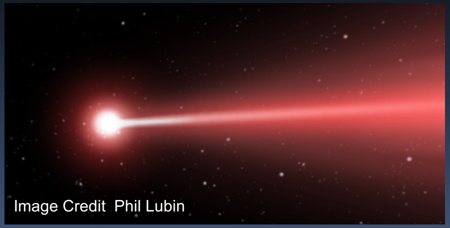
Radioisotope Thermal electric Generators (RTGs)



Fission Reactors



Directed Energy



Fusion?, Anti-matter?

Things to be Mindful of When Designing an Electric Propulsion System

- Thrust, power, Isp
- Input power range
- Input voltage
- Propellant through capability (life)
- Exhaust plume characteristic
- Specific mass

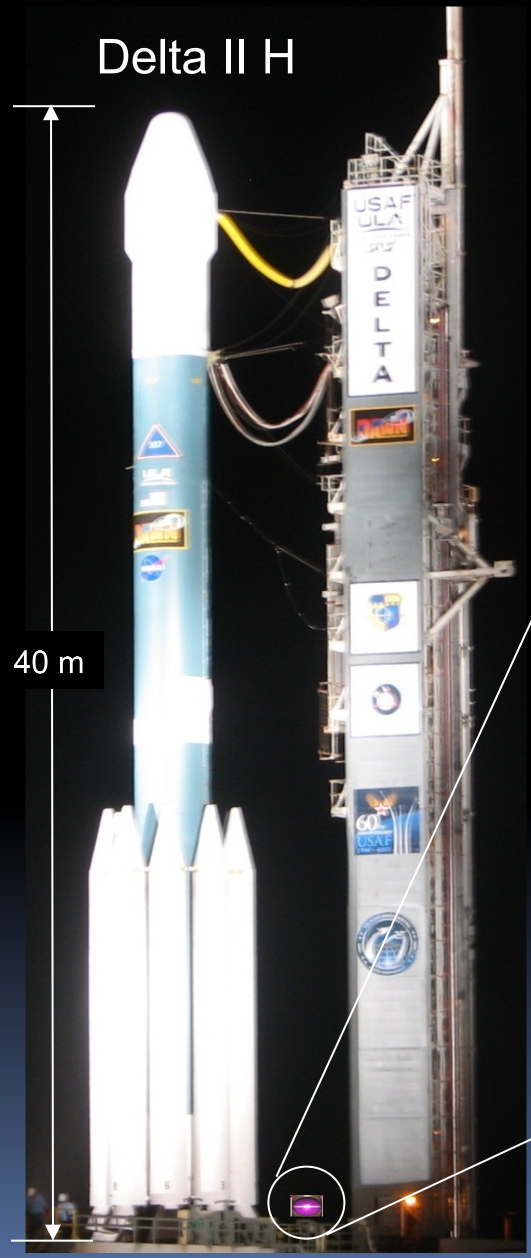
The "Power" of Electric Propulsion

- The launch vehicle:
  - 40-m high
  - 230,000 kg

- The Ion Propulsion System (IPS):
  - < 2-m high
  - 555 kg

- The IPS operated ~75,000 times longer than the launch vehicle

EP Trajectories spread out the energy in time to reduce the required power

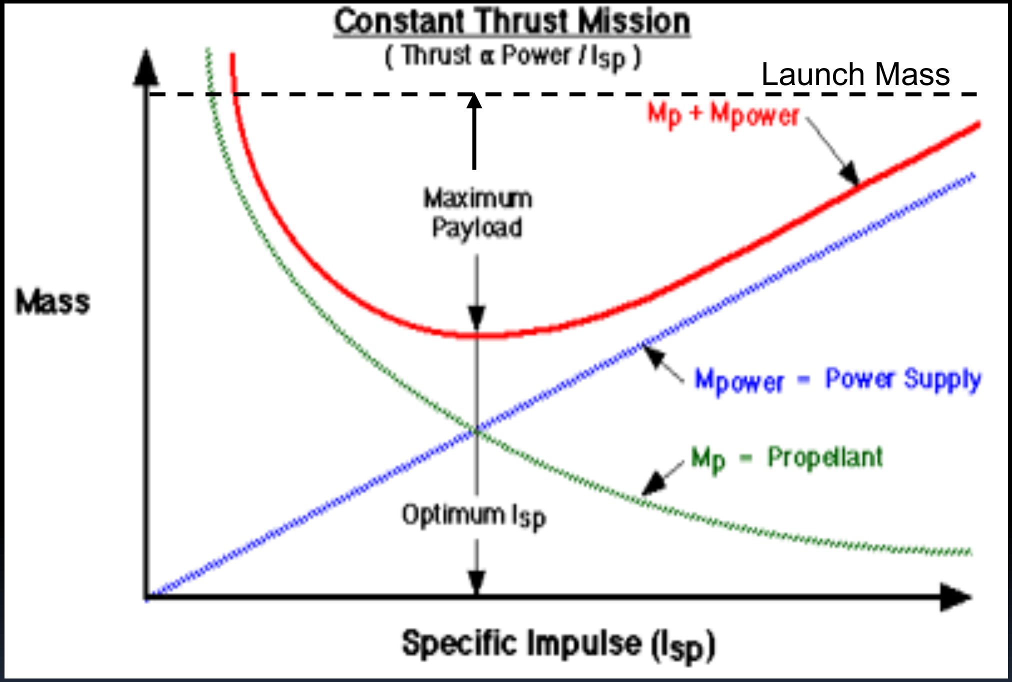


The Dawn IPS provided as much DV to the spacecraft as the launch vehicle

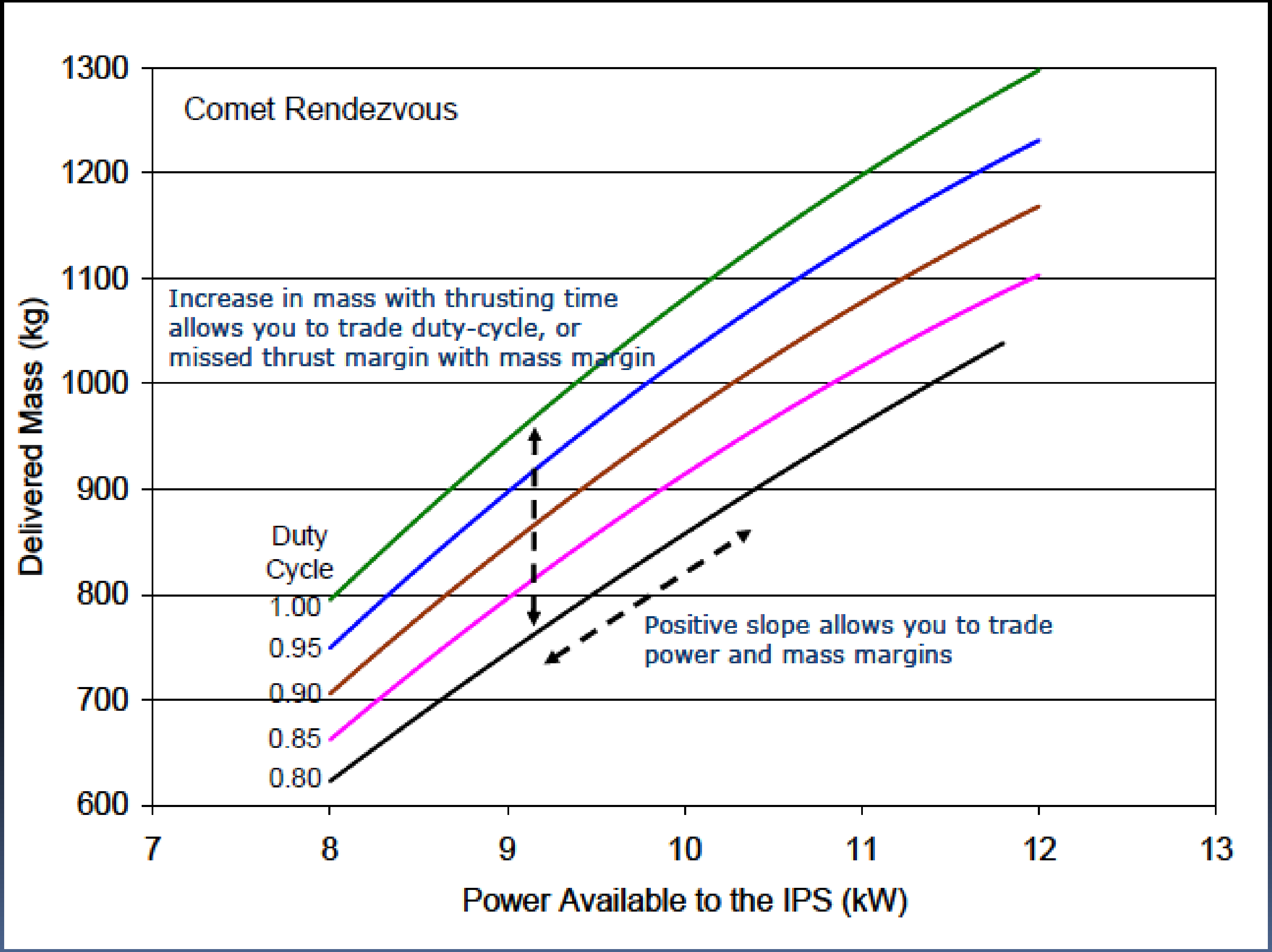
The 60-gallon propellant tank for the Dawn Ion Propulsion System (IPS) would fit in the trunk of your car

If high *Isp* is good, why not run at as high an *Isp* as possible?

- The propellant mass decreases exponentially with *Isp* (rocket equation)
- The power subsystem mass increases linearly with specific impulse
- This results in an optimum specific impulse for electric propulsion systems/missions



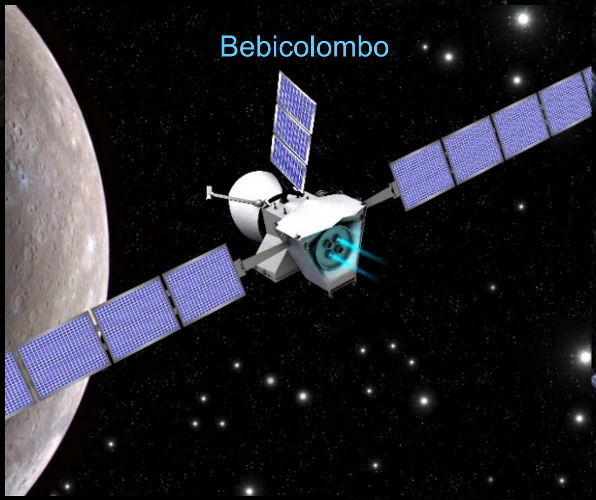
EP Enables Trades between Mass, Power, and Duty Cycle Margins



Deep Space Missions using Electric Propulsion

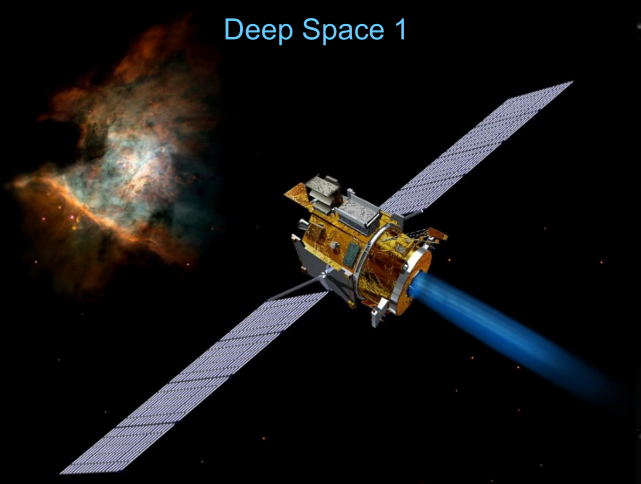
Dawn

Bebicolombo



Hayabusa 1

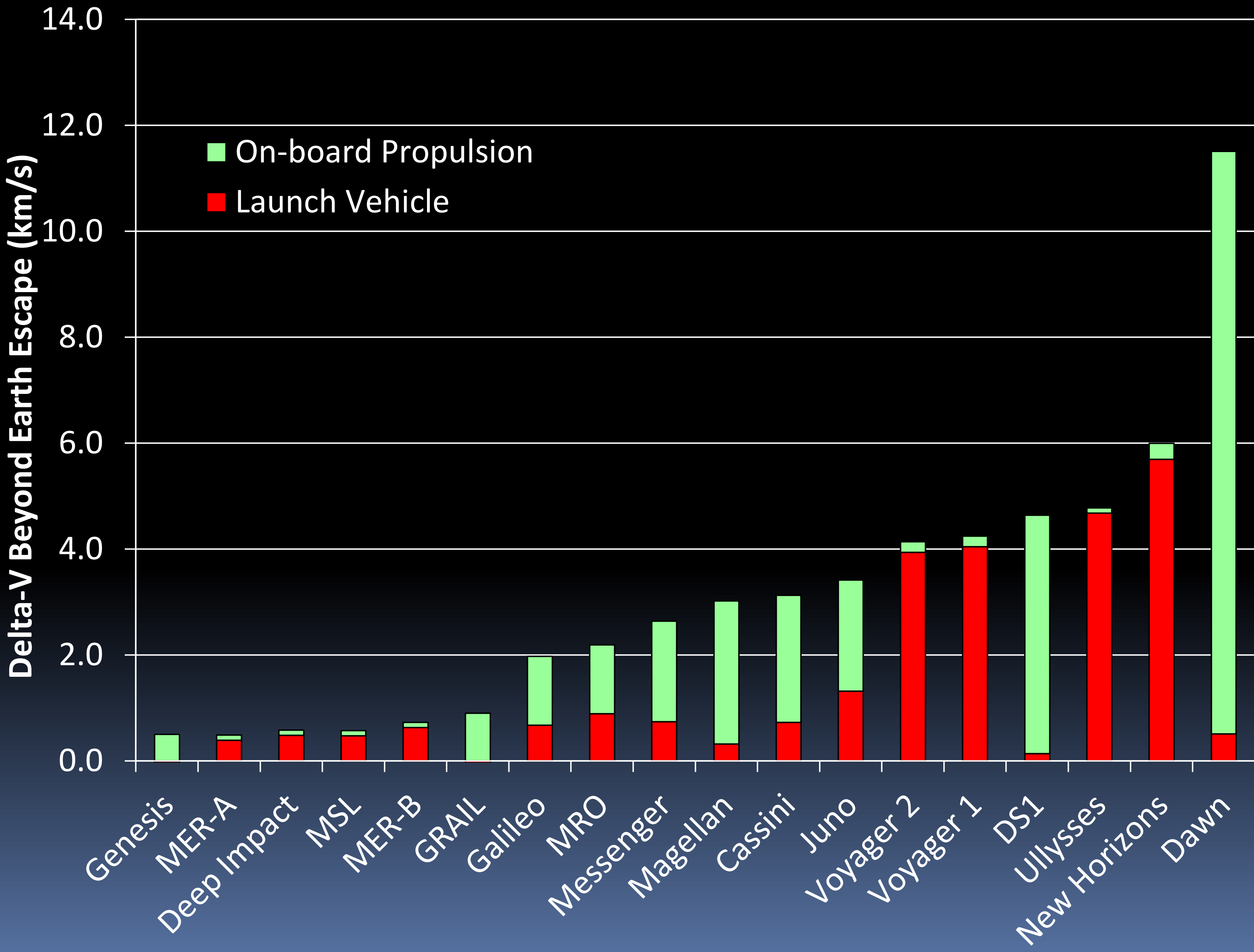
Deep Space 1

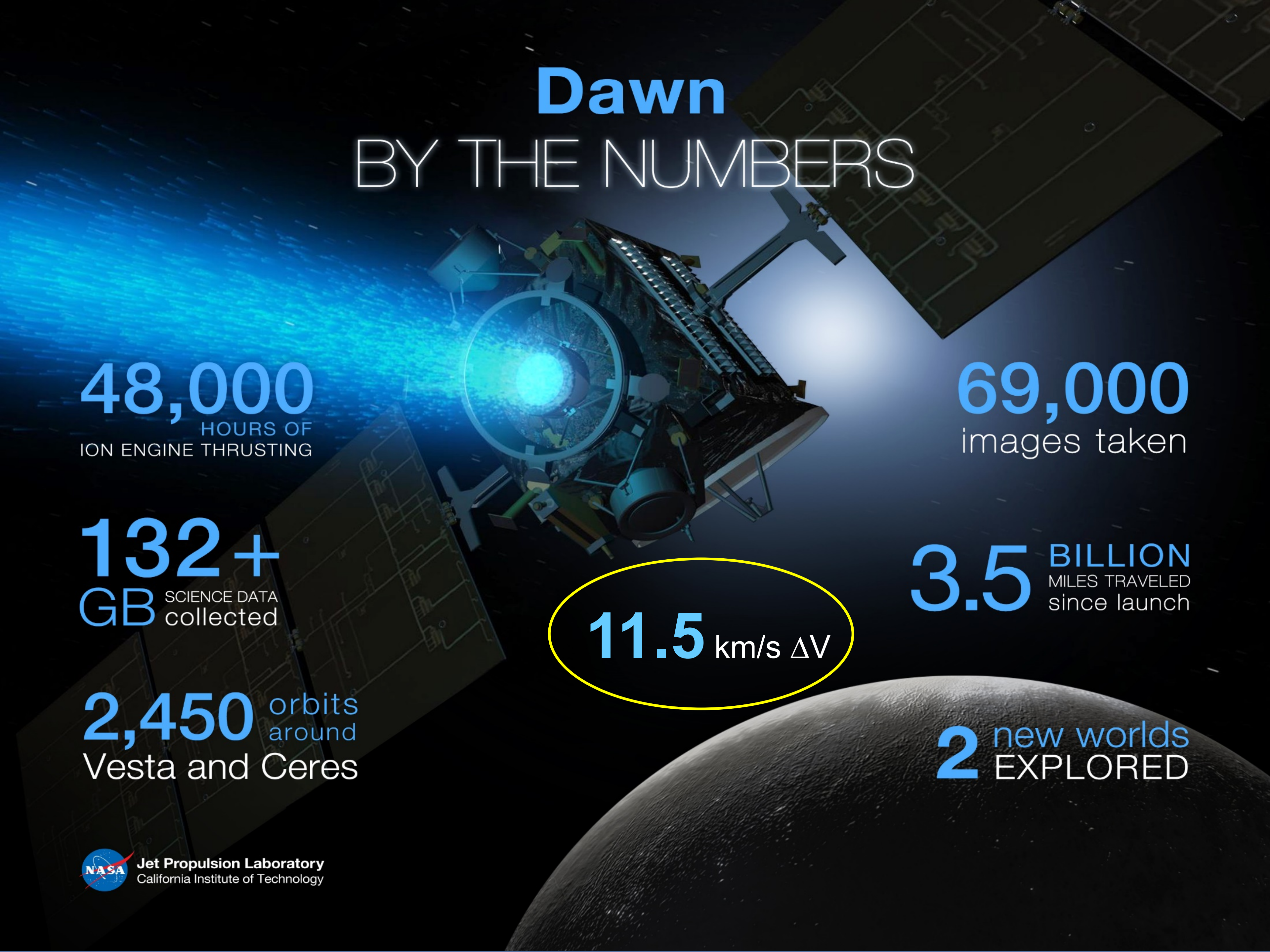


SMART-1

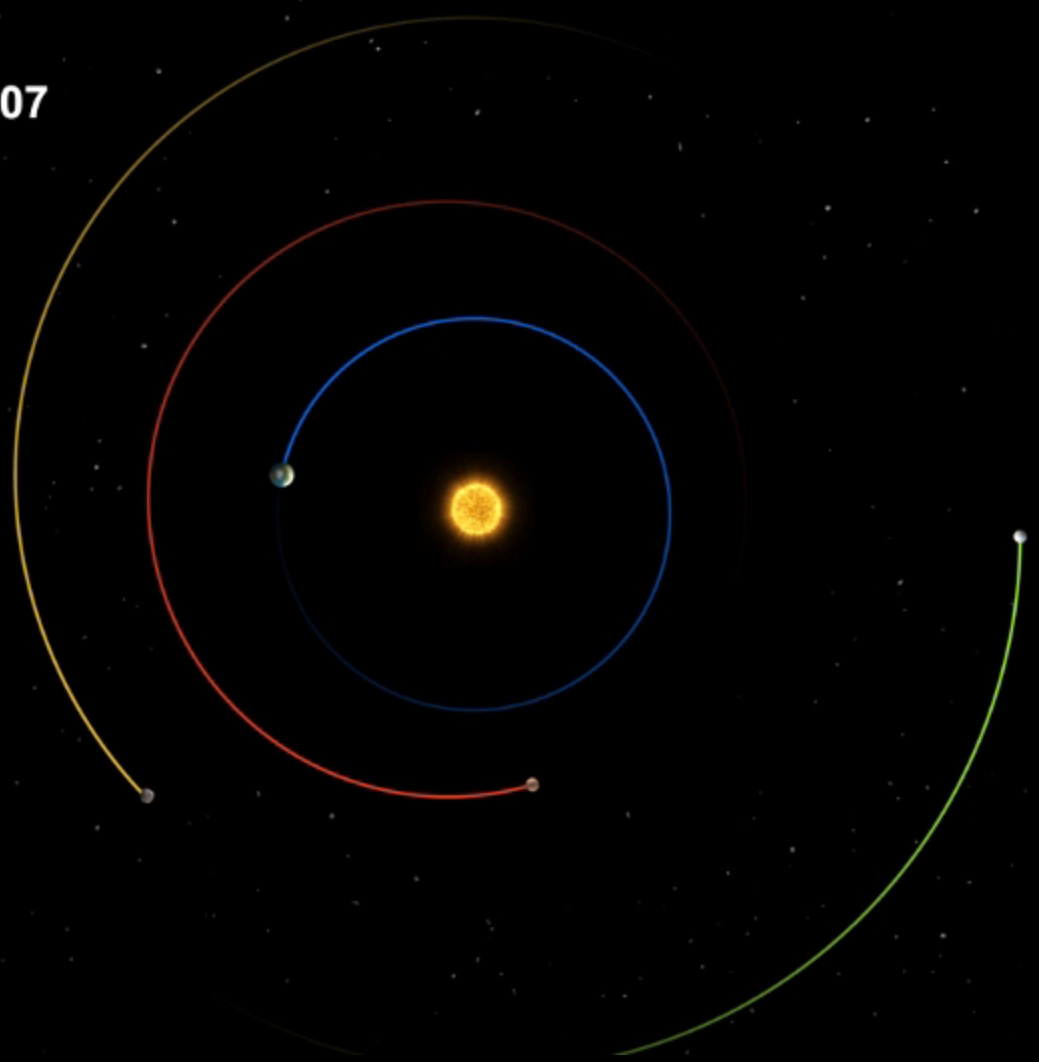
Hayabusa 2

ΔV Beyond Earth Escape




Dawn
BY THE NUMBERS
48,000
HOURS OF
ION ENGINE THRUSTING
69,000
images taken
132+
GB SCIENCE DATA
collected
3.5 BILLION
MILES TRAVELED
since launch
11.5 km/s ΔV
2,450 orbits
around
Vesta and Ceres
2 new worlds
EXPLORED
Jet Propulsion Laboratory
California Institute of Technology

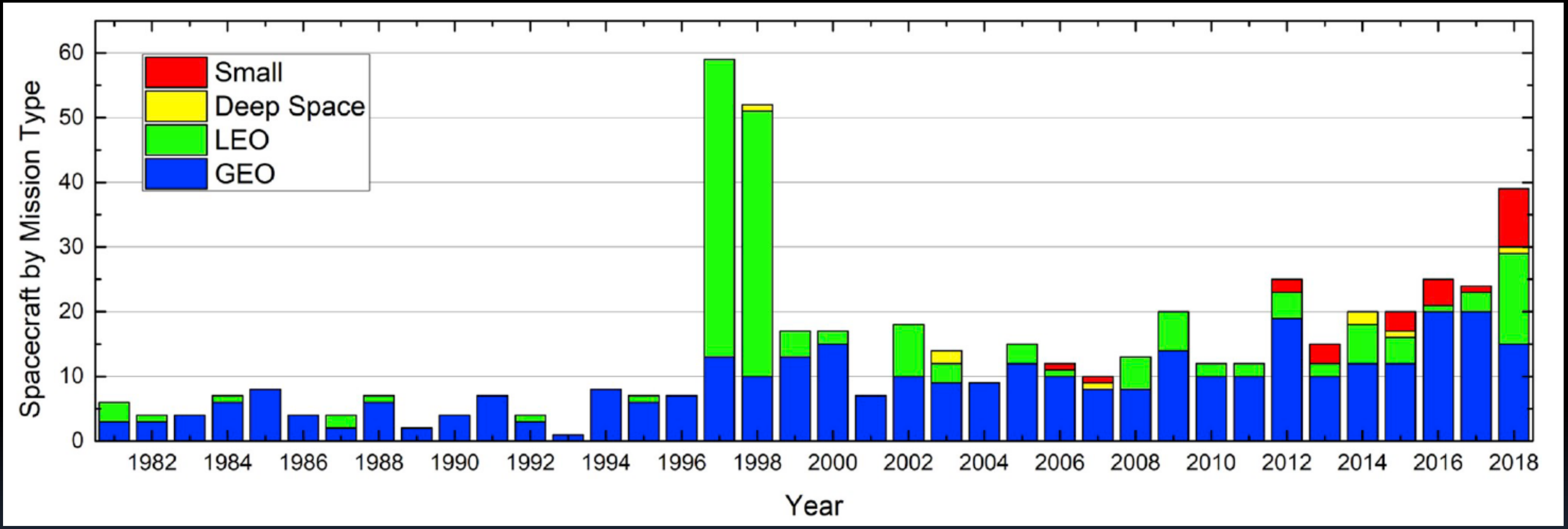
Mar 2007



Commercial Spacecraft

Satellites with EP

- Nearly 600 spacecraft have been launched with electric propulsion
- Most are commercial satellites



Lev, D., et al, "The technological and commercial expansion of electric propulsion," *Acta Astronautica* 159 (2019) 213-227.

JPL

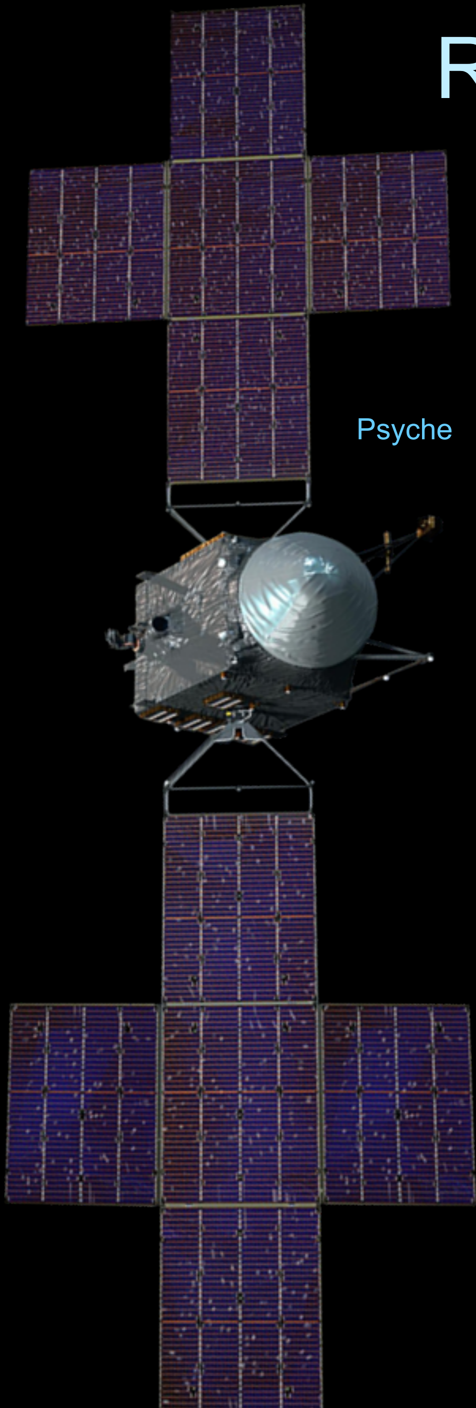
Boeing All-Electric Satellites

Future

Electric Propulsion has the Potential to Impact an Impressive Range of the Nation's Space Interests

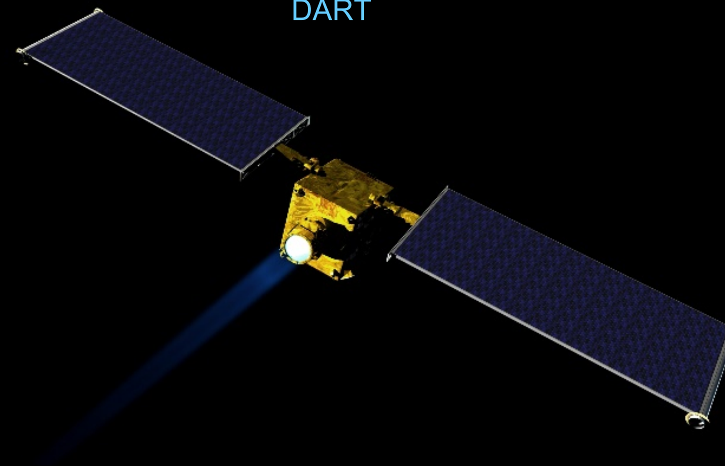
- LEO Constellations
- Robotic Science Missions
- Human Exploration Missions
- Planetary Defense
- Asteroid Mining
- Rapid Transportation Throughout the Solar System

Robotic Science Missions



Psyche

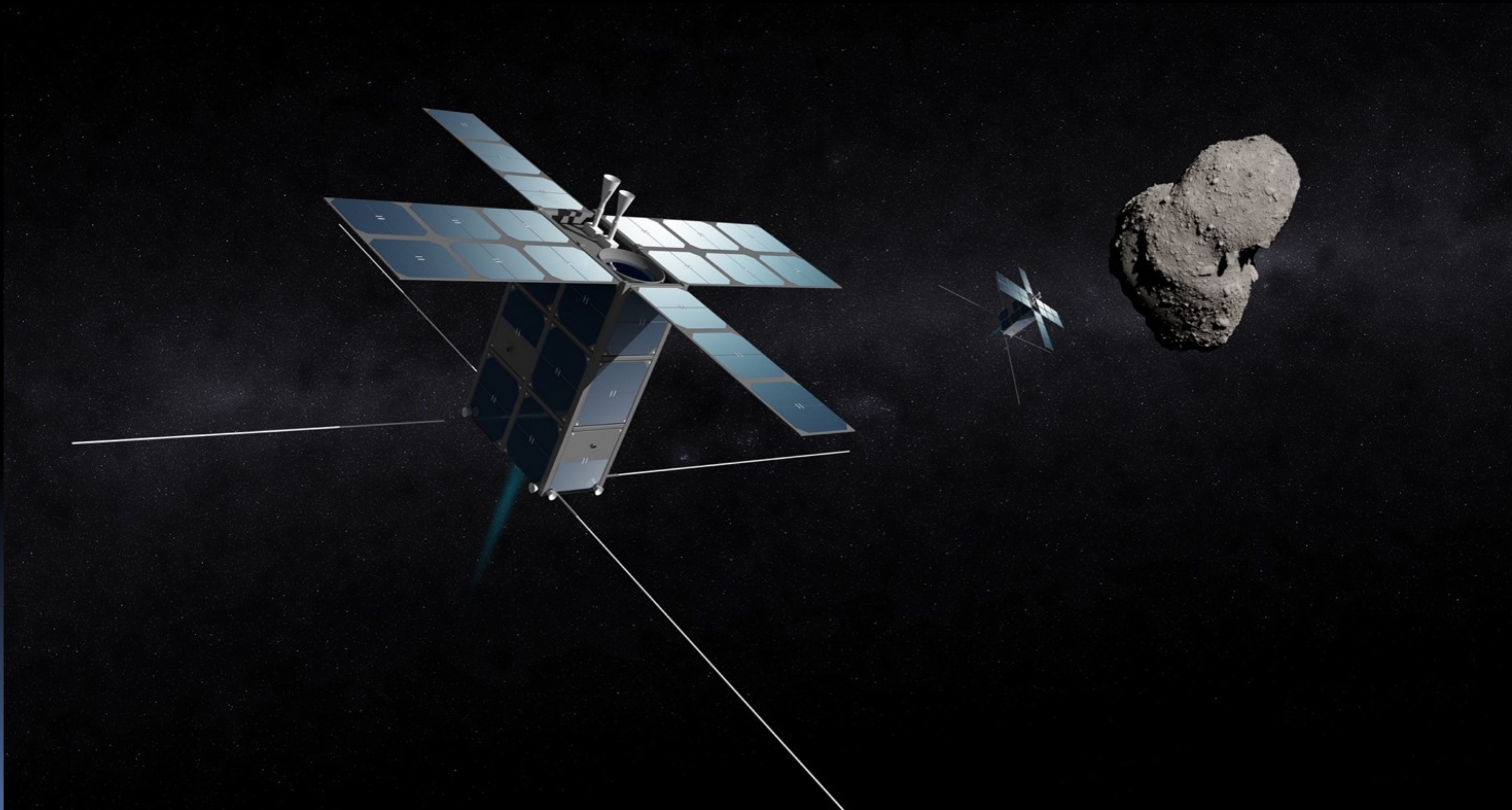
DART



CAESAR

Pre-Decisional Mission Concepts

Deep Space SmallSats (< 100 kg)



Mission Concept from Deep Space Industries, Inc.

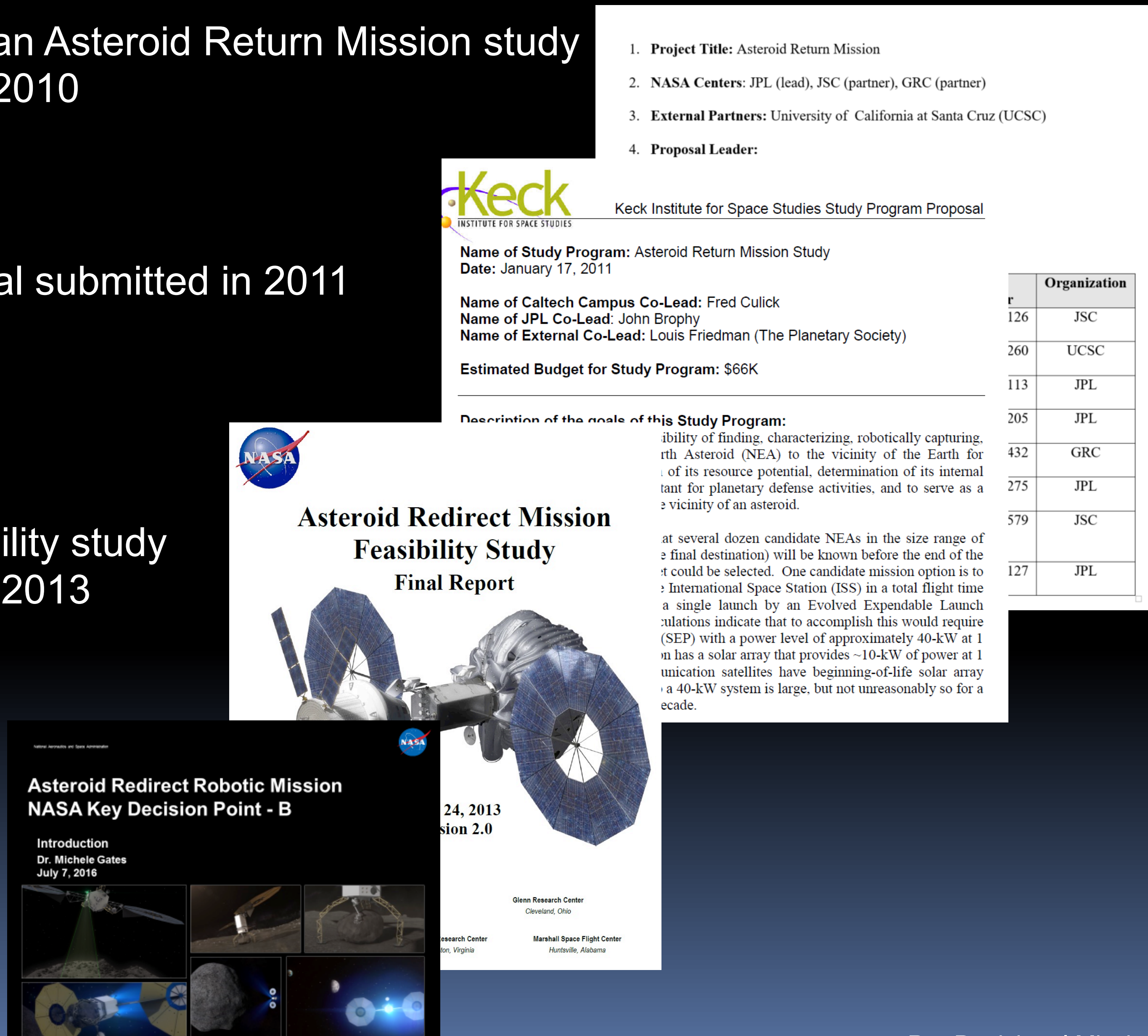
Asteroid Retrieval Mission

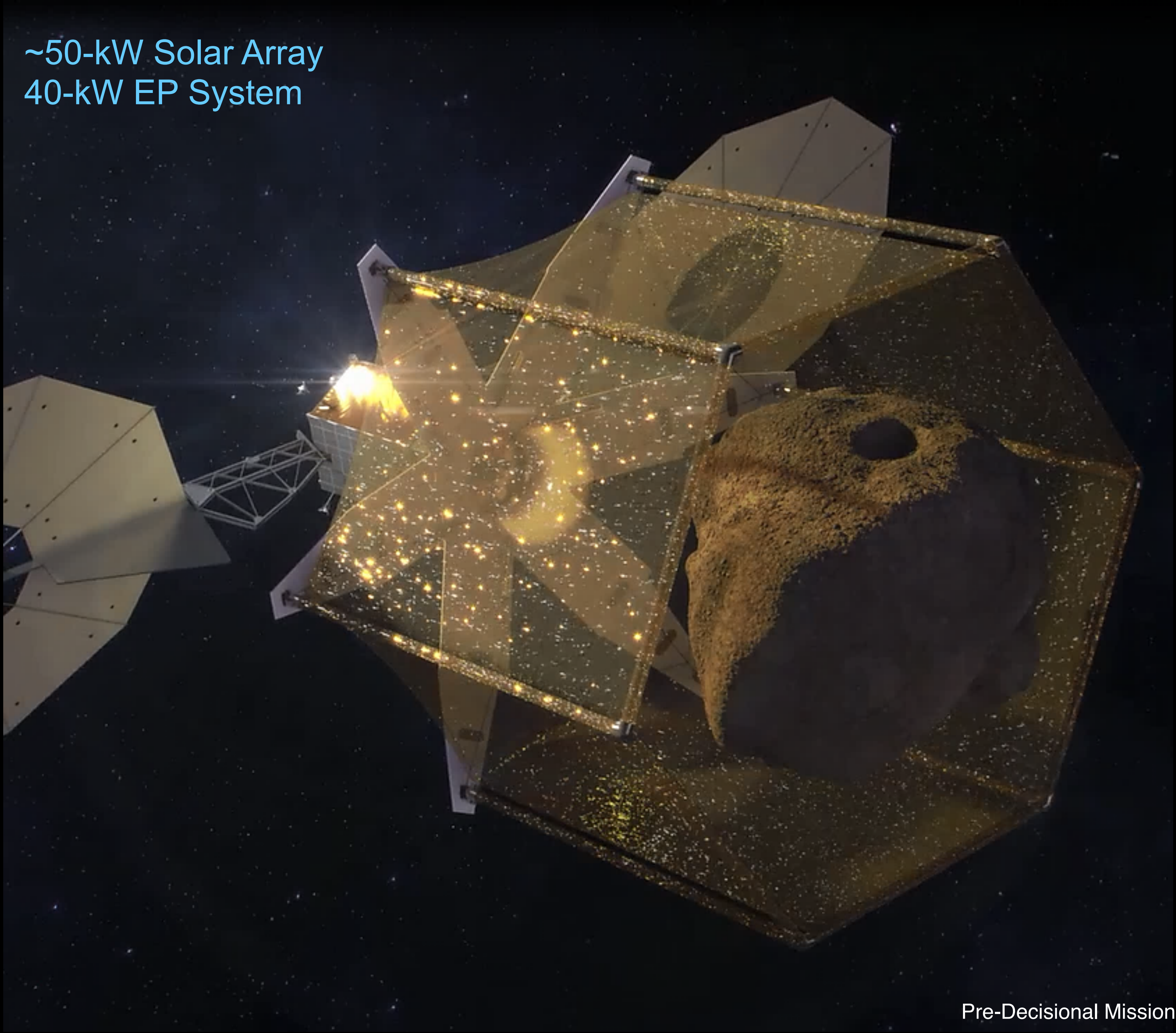
Proposal for an Asteroid Return Mission study submitted in 2010

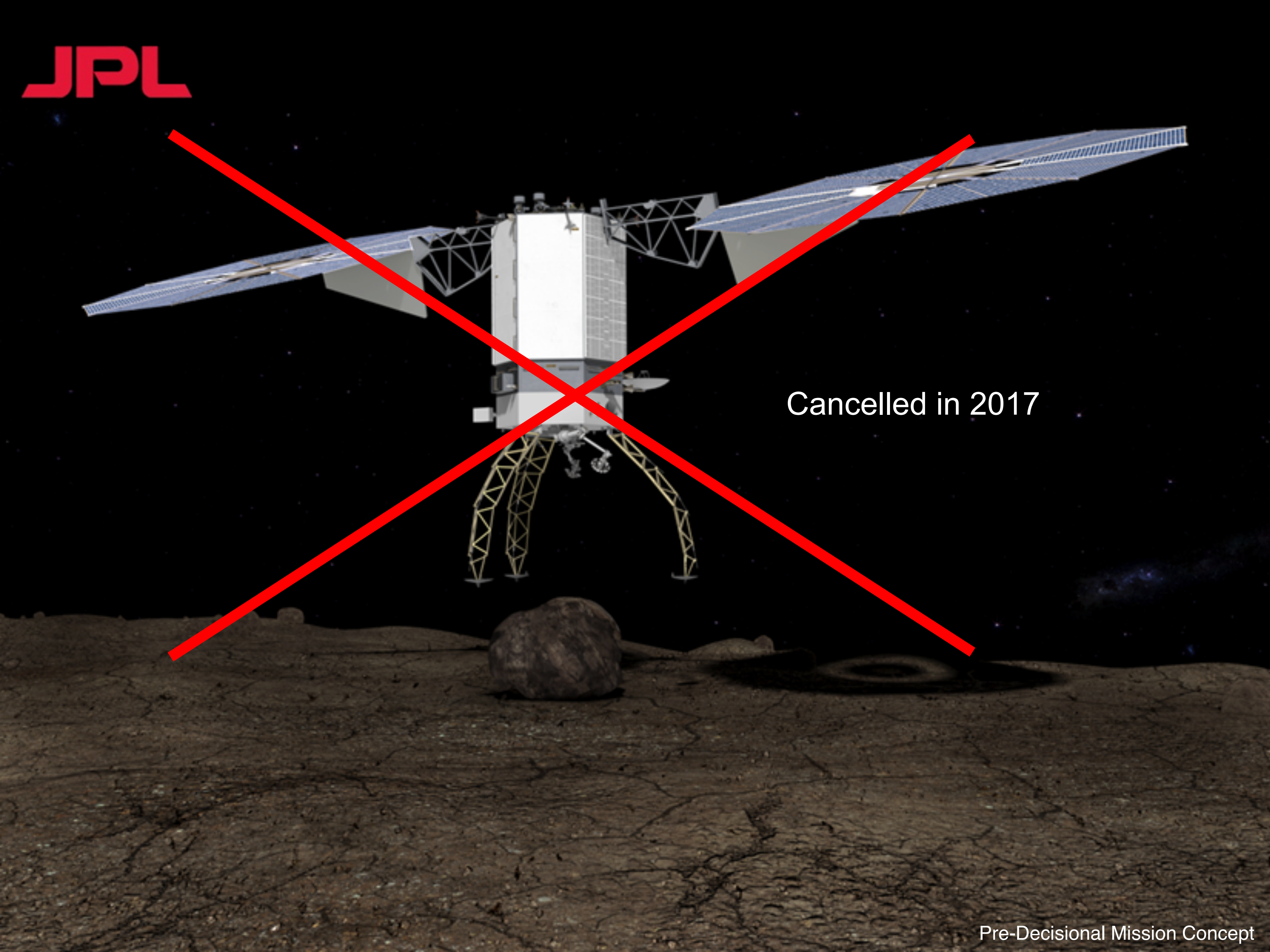
KISS Proposal submitted in 2011

NASA Feasibility study completed in 2013

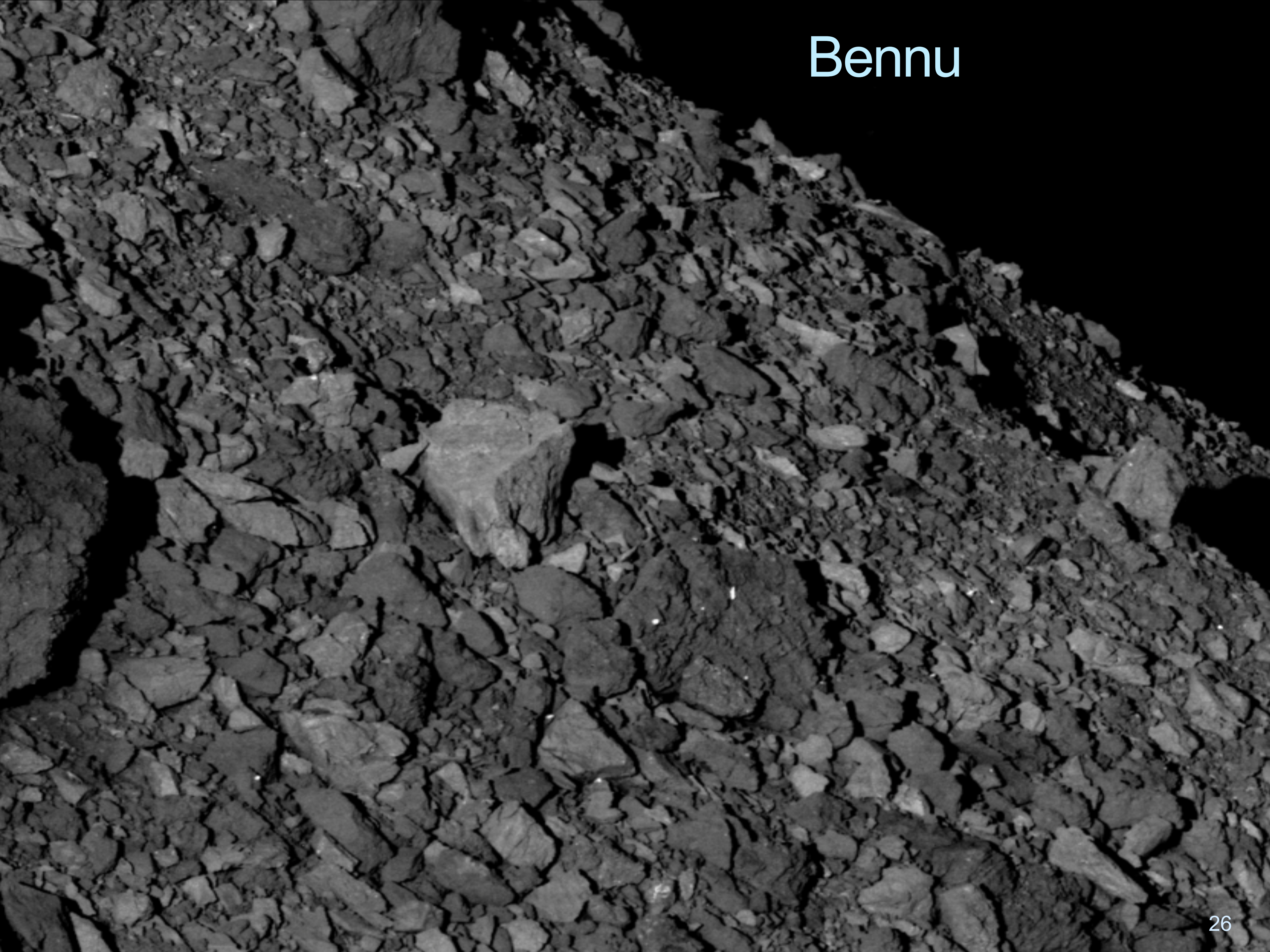
Phase B started 2016



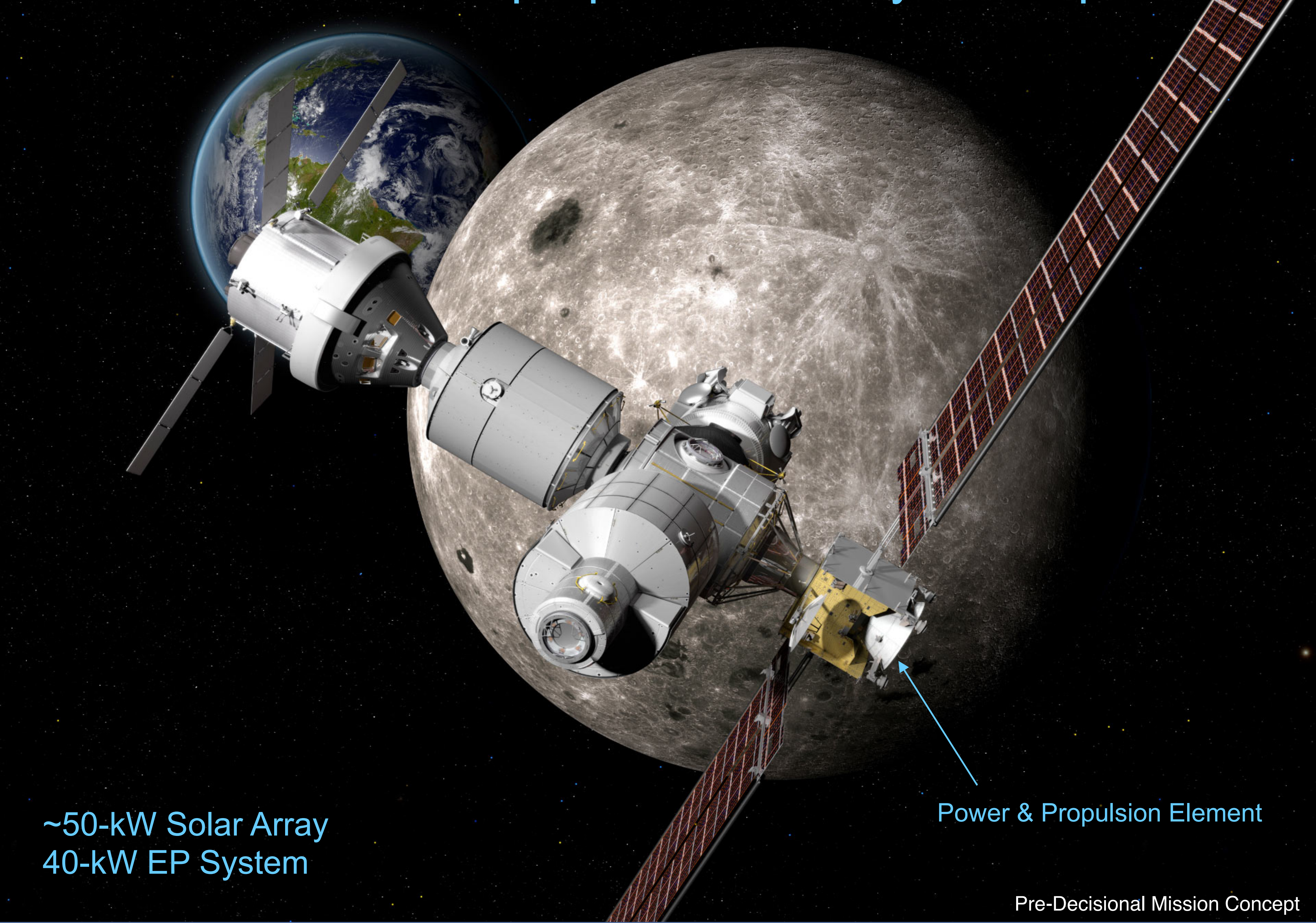

~50-kW Solar Array
40-kW EP System
Pre-Decisional Mission Concept


JPL
Cancelled in 2017
Pre-Decisional Mission Concept

Bennu



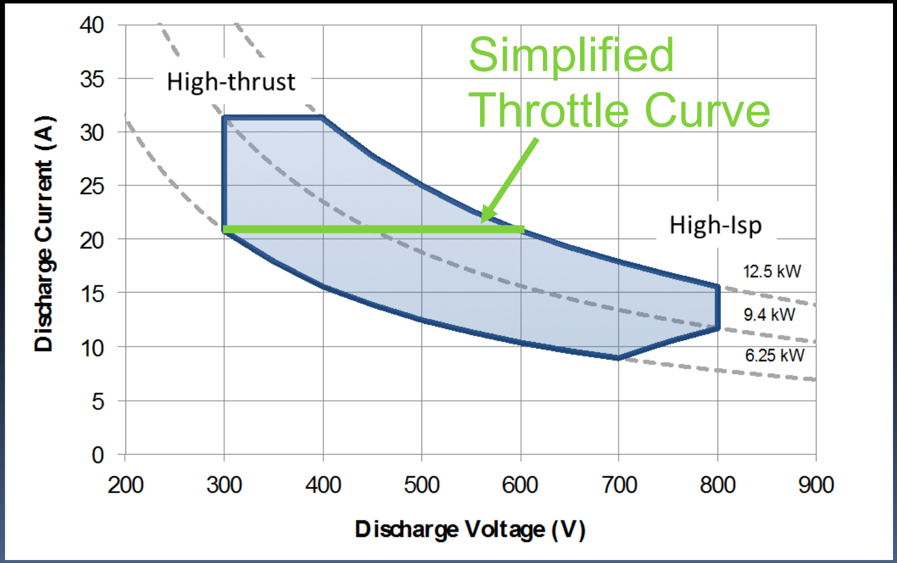
NASA's Deep Space Gateway Concept

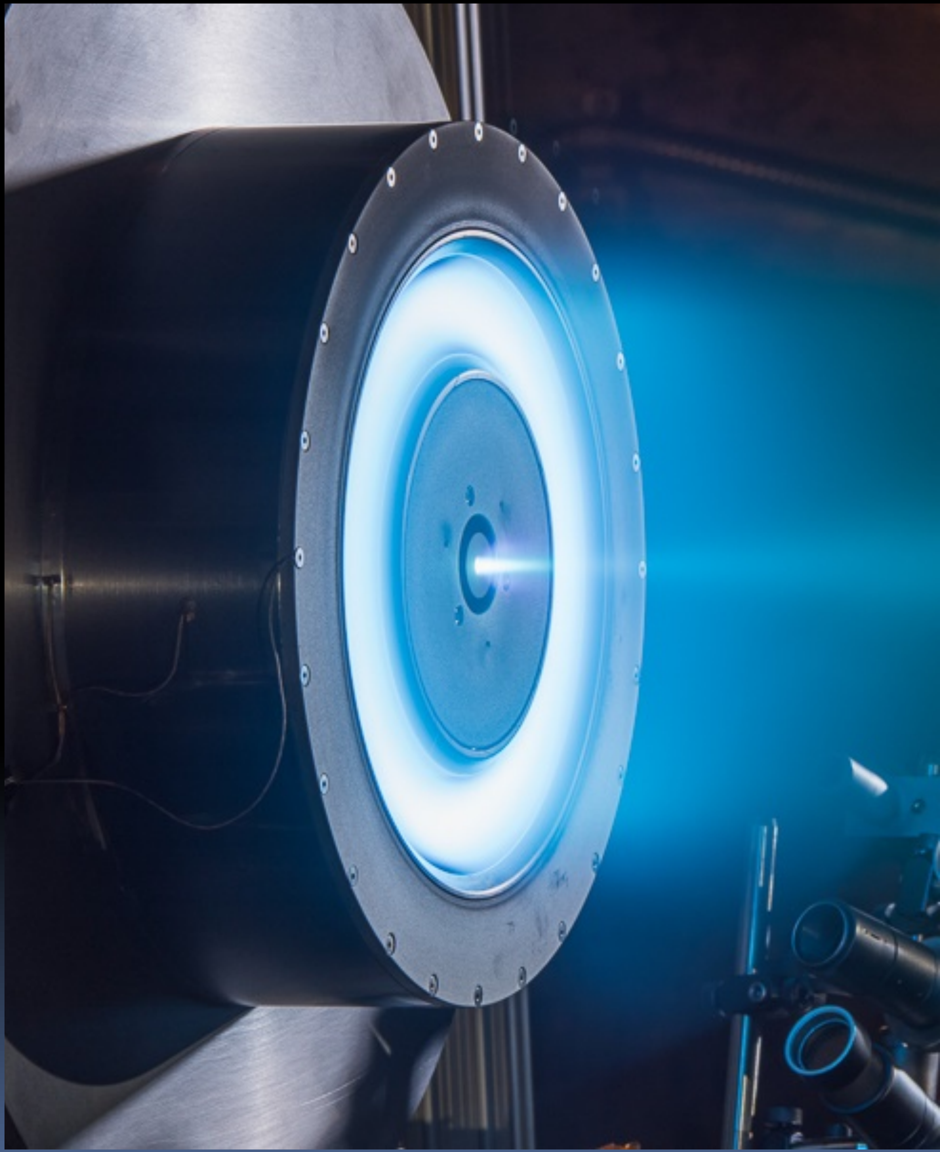


High-power Hall Thrusters

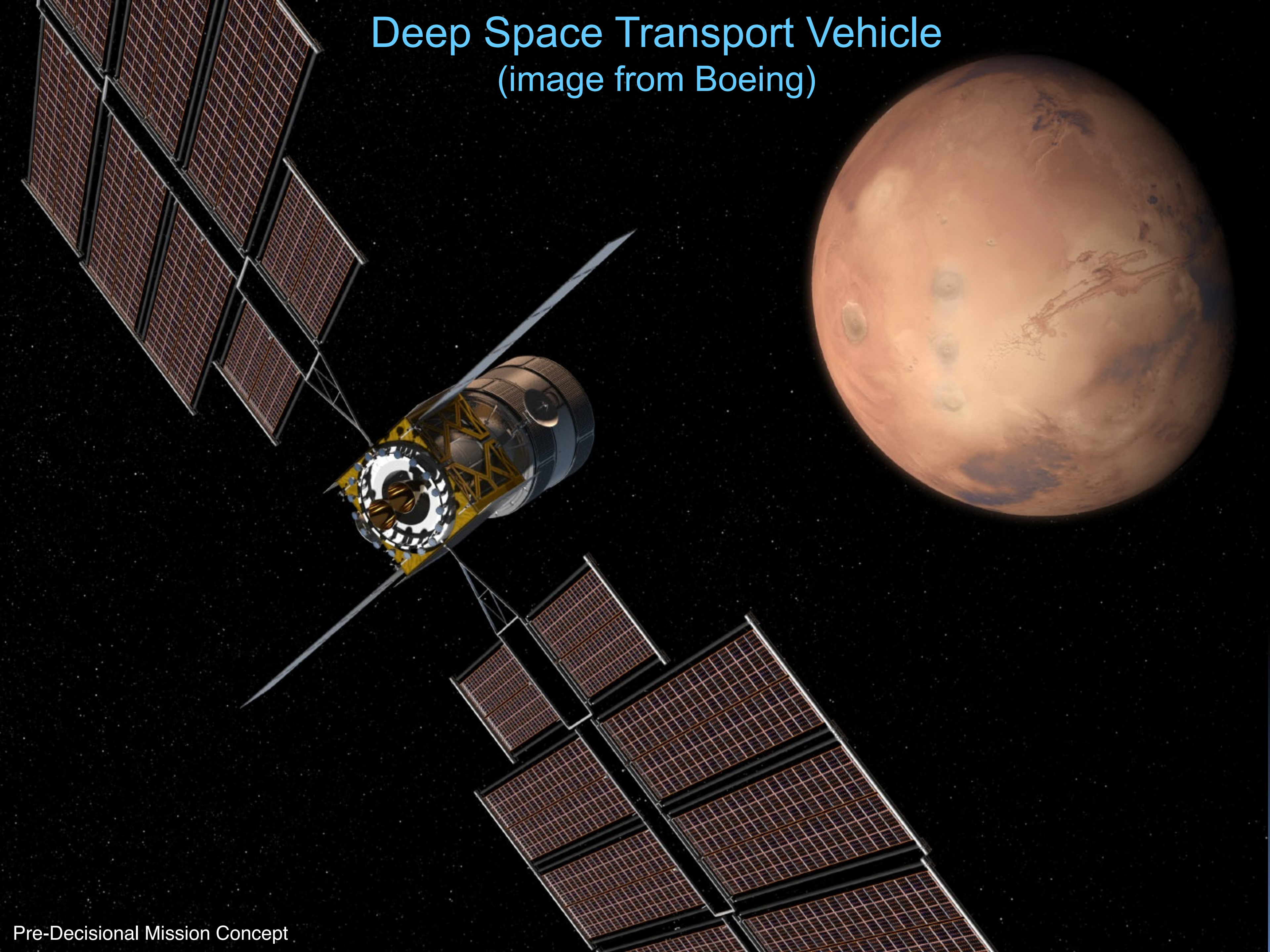
HERMES Hall Thruster

- 12.5-kW, 2600-s Hall Thruster
- Currently under development by NASA / Aerojet Rocketdyne





Deep Space Transport Vehicle
(image from Boeing)



Pre-Decisional Mission Concept

Very High-power Hall Thrusters

NEXTStep 100-kW-class nested-Hall thruster

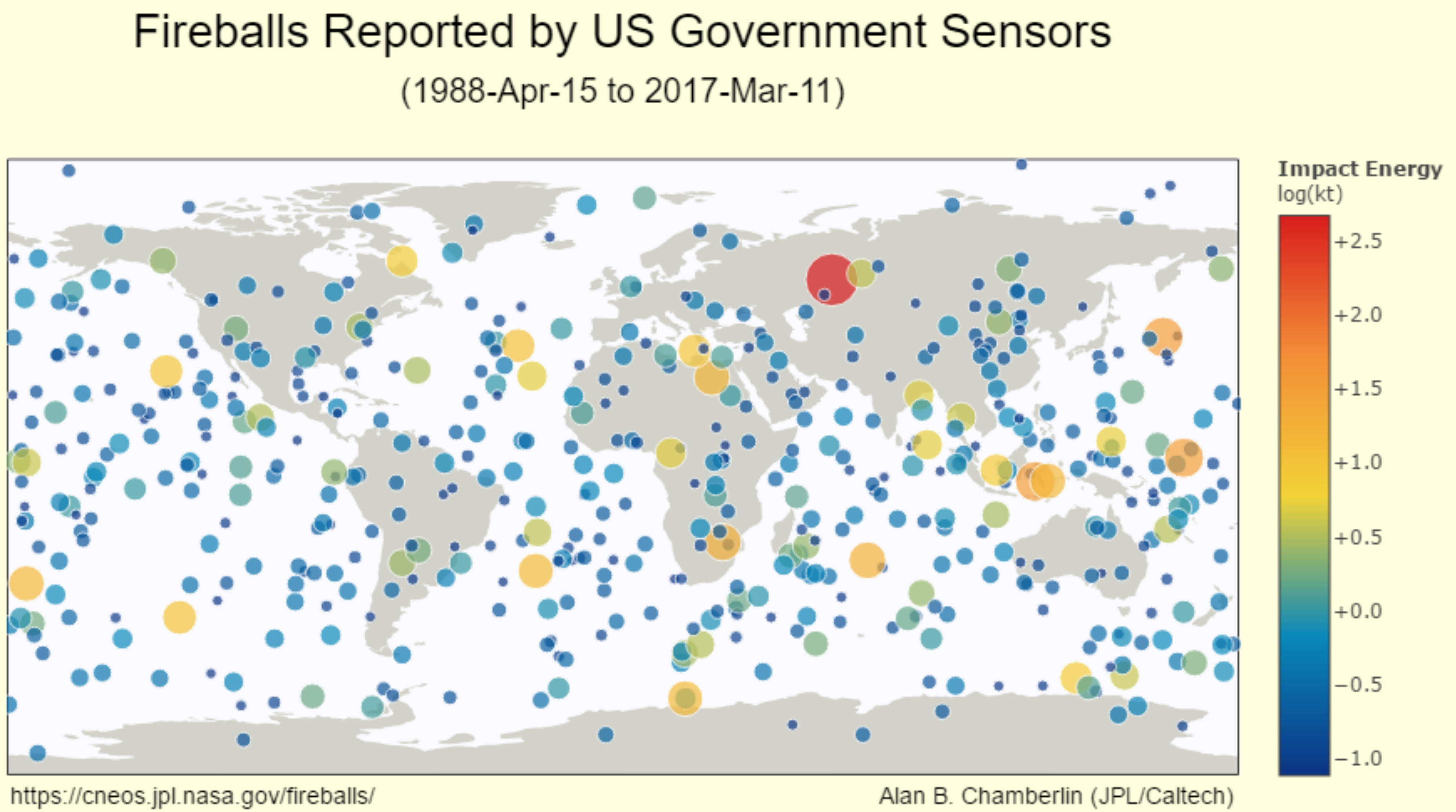
Planetary Defense

After discovery, this becomes primarily a propulsion problem

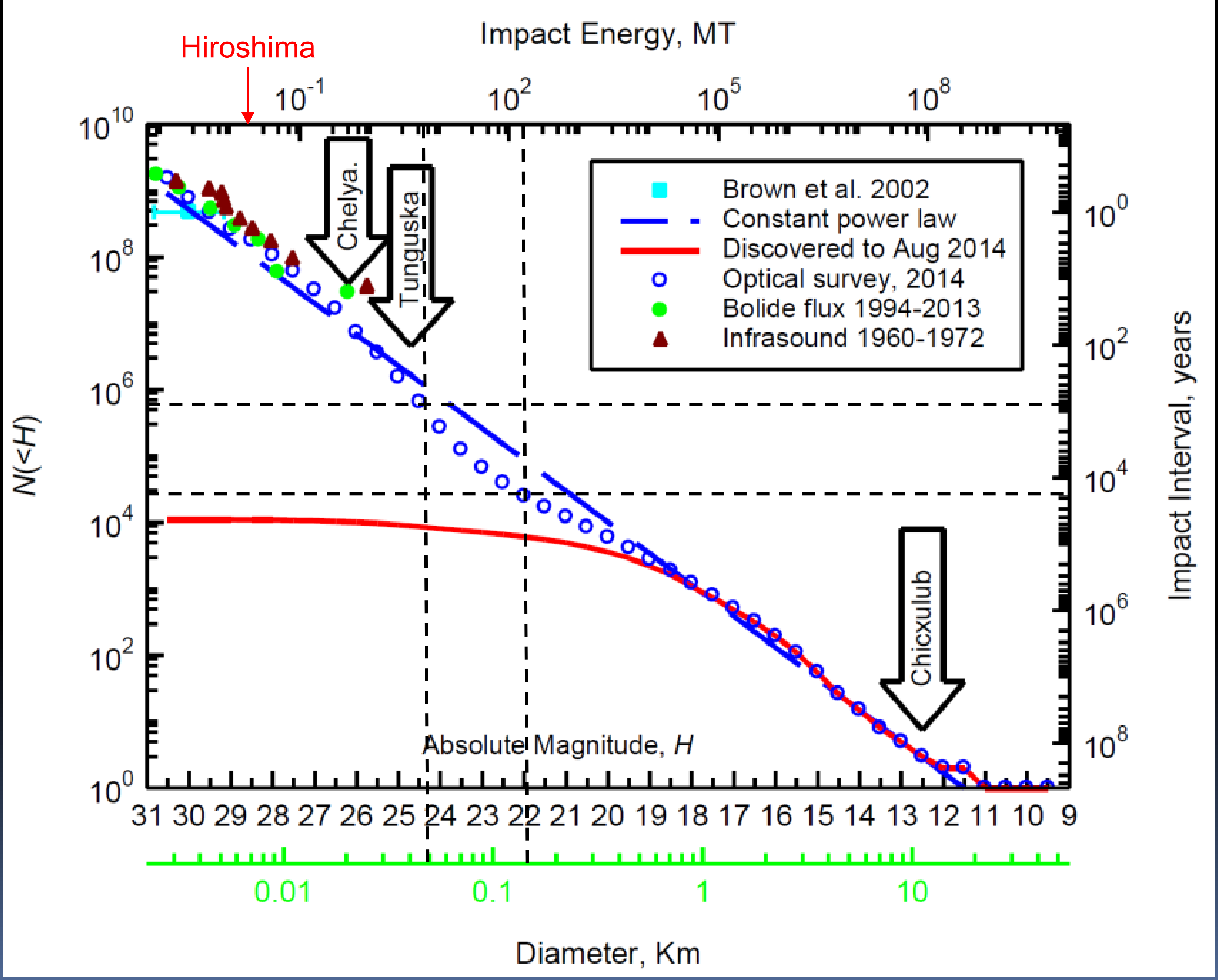
NEVER FORGET

12/21/65000000 b.c.

What size asteroids do we need to be concerned with?

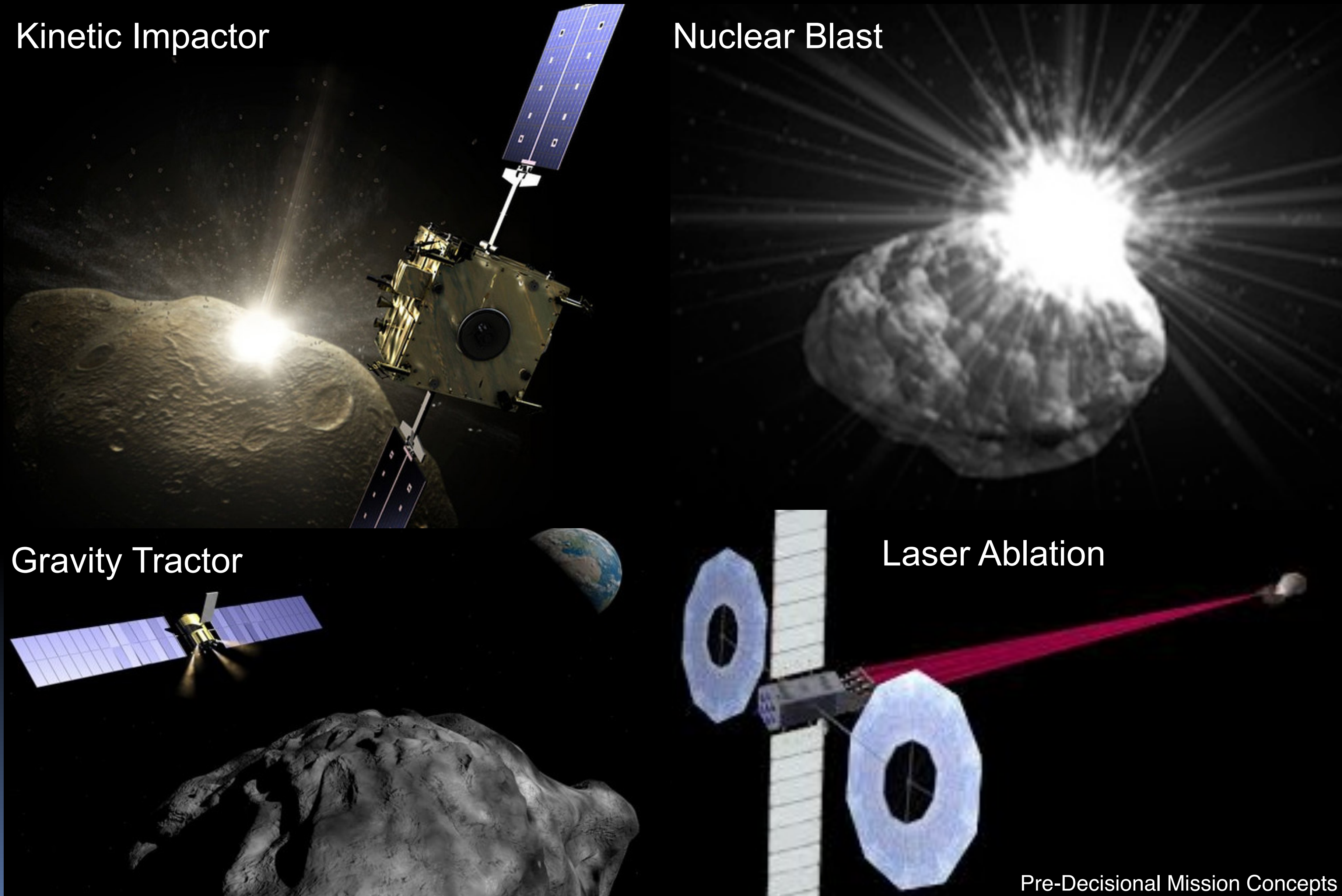


Most likely threat objects may turn out to be in the 50 m to 140 m dia



Boslough, M., Brown, P., and Harris, A., "Updated Populsion and Risk Assessment for Airburst from Near-Earth Objects (NEOs)," 2015 IEEE Aerospace Conference, Big Sky, MT.

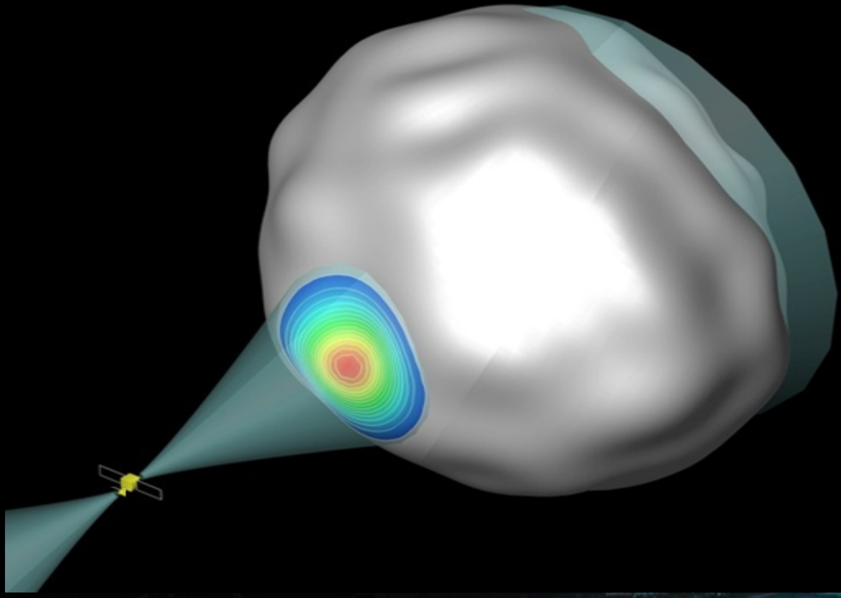
Planetary Defense Techniques

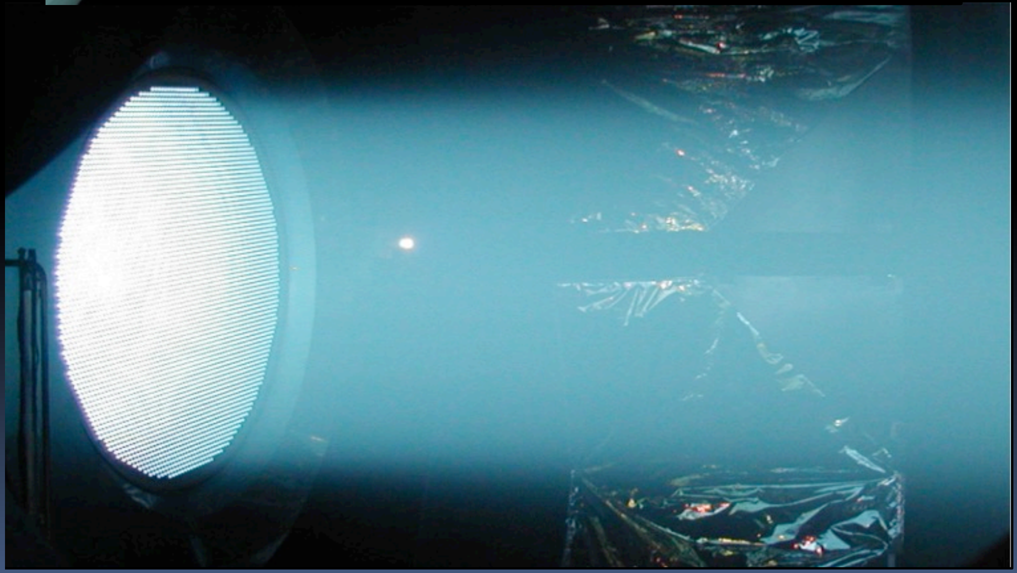


Ion Beam Deflection

Key Features

- Ions act as kinetic impactors
- Applied force is independent of the asteroid characteristics
- Can engineer the applied force (power) and propellant usage (specific impulse)



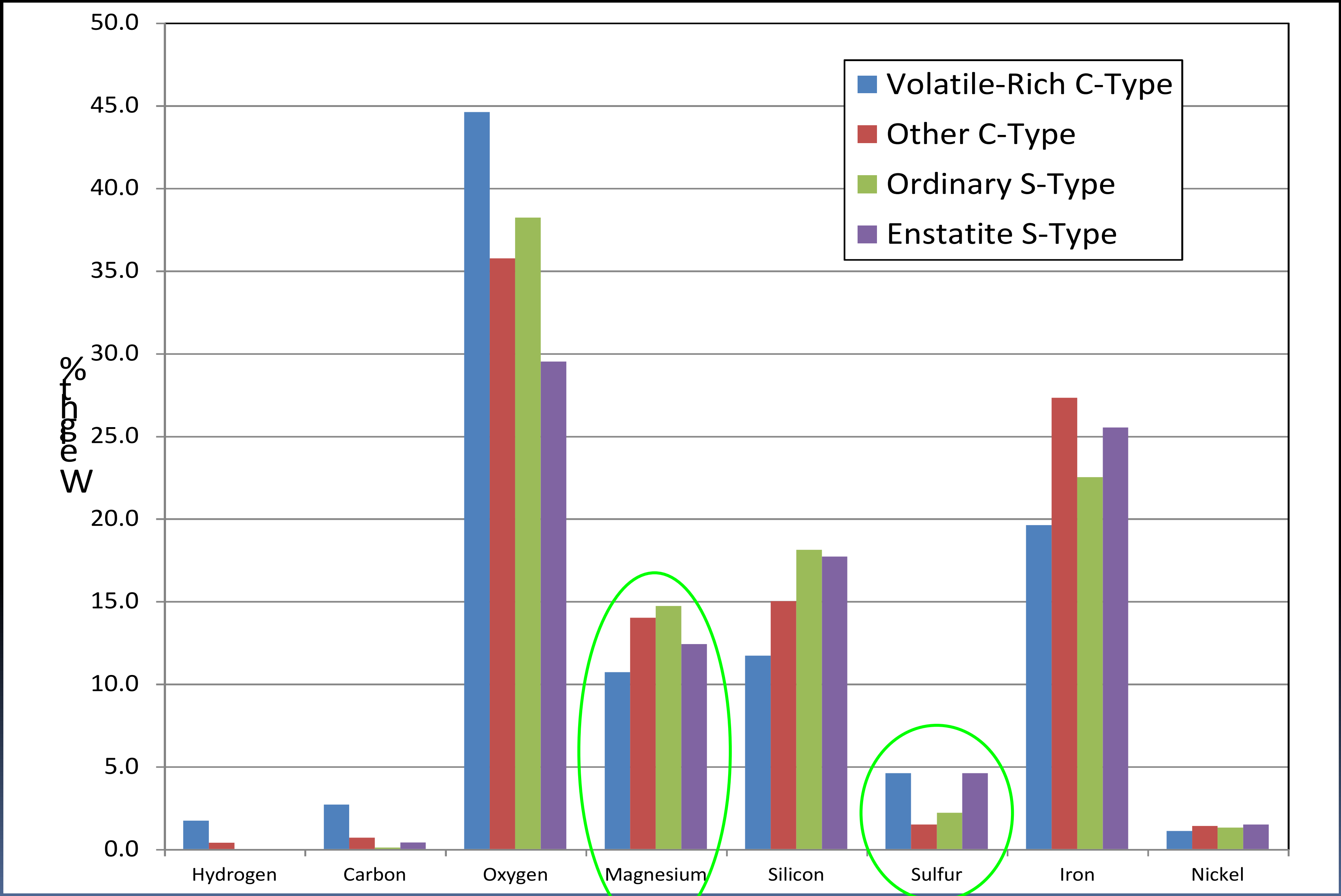


Ion Beam Deflection Well Suited to Deflecting 50 to 140-m dia. Objects

Asteroid Mining

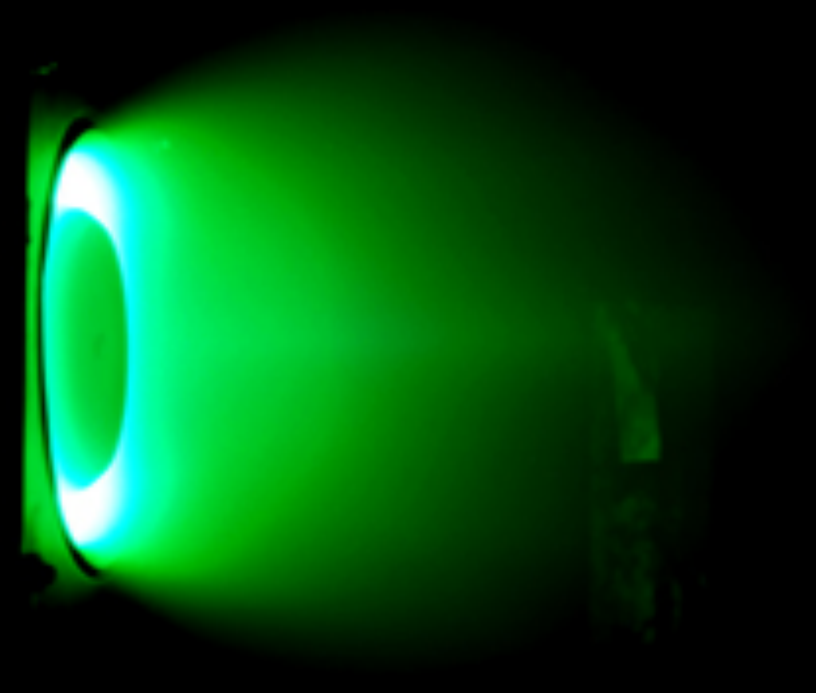
- Has long been recognized as a propulsion problem
- Probably only feasible in the long run if you can use asteroid-derived propellants

In Space Resource Utilization



Hutchison, R., "Meteorites, A Petrologic, Chemical and Isotopic Synthesis," *Cambridge University Press*, 2004, ISBN 0 521 47010 2.

Asteroid-Derived Hall Thruster Propellants



A magnesium-fueled Hall thruster
from Michigan Technological University

	Molecular Weight	Melting Point	Boiling Point	Ionization Energy (eV)			Vapor Pressure			
	(AMU)	(C)	(C)	1st	2nd	Temperature	1 Pa	10 Pa	100 Pa	1000 Pa
Magnesium	24.31	650	1091	7.65	15.04	T (K)	701	773	861	971
Sulfur	32.06	115	445	10.36	23.34	T (K)	375	408	449	508
Xenon	131.3	-112	-108	12.13	21.21	T (K)	83	92	103	117

Rapid Transportation Throughout the Solar System

Three Key Features of an Architecture to Go Fast

1

Kilometer-scale Laser

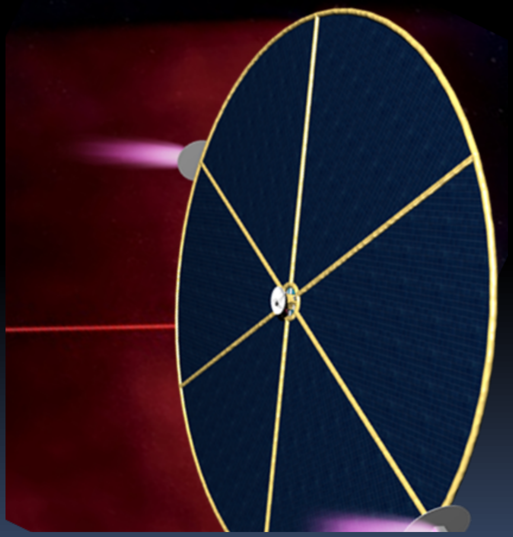
Don't carry the power source—laser beam power to the spacecraft


Image Credit Phil Lubin

2

Light-weight PV Collector

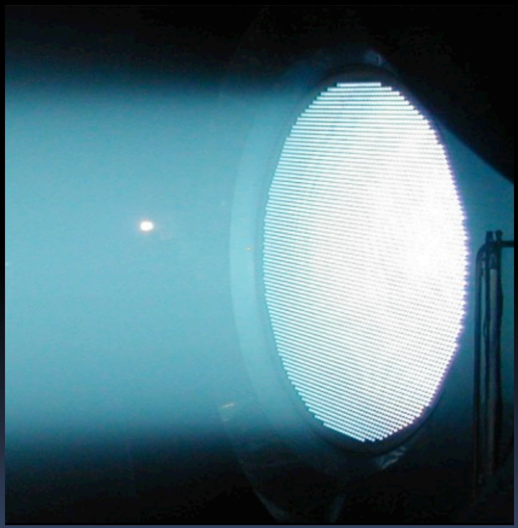
Collect the laser power and convert it to electricity to power the ion drive system



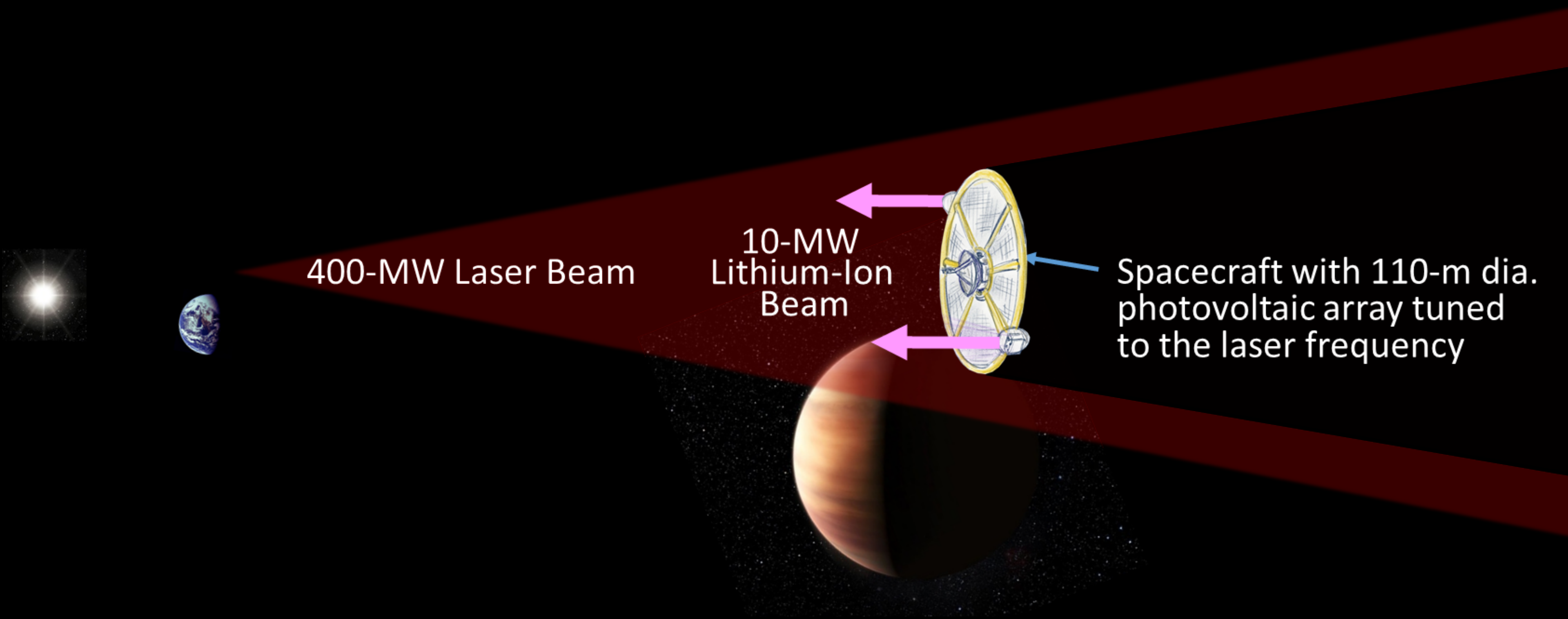
3

Ultra-high Isp Thruster

Increase the exhaust velocity by a factor of 10 over the best ion engines today



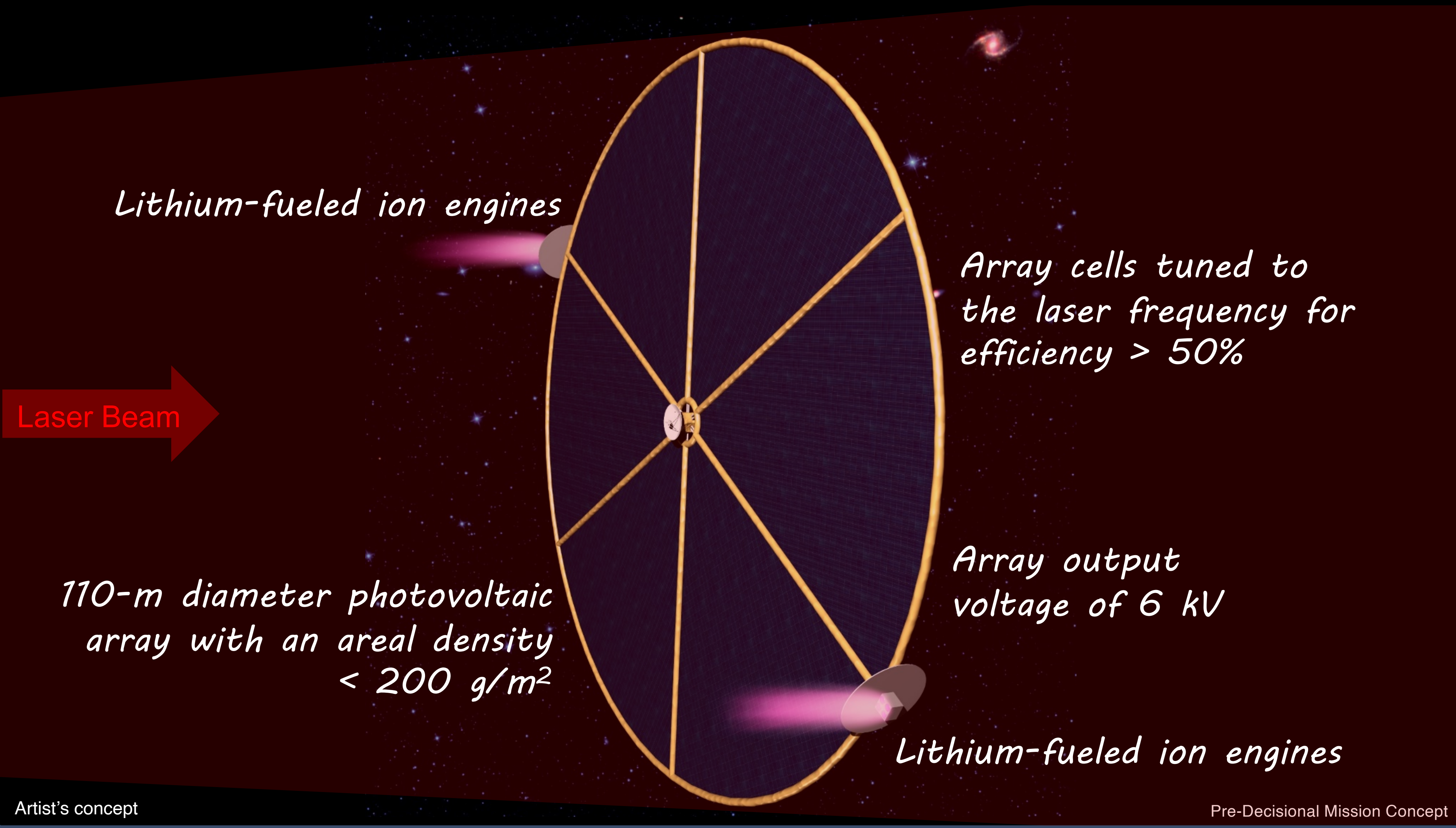
Artist's concepts



A space-based laser beams power to a lithium-fueled, ultra-high specific impulse vehicle to enable rapid transportation throughout the solar system

Artist's concept

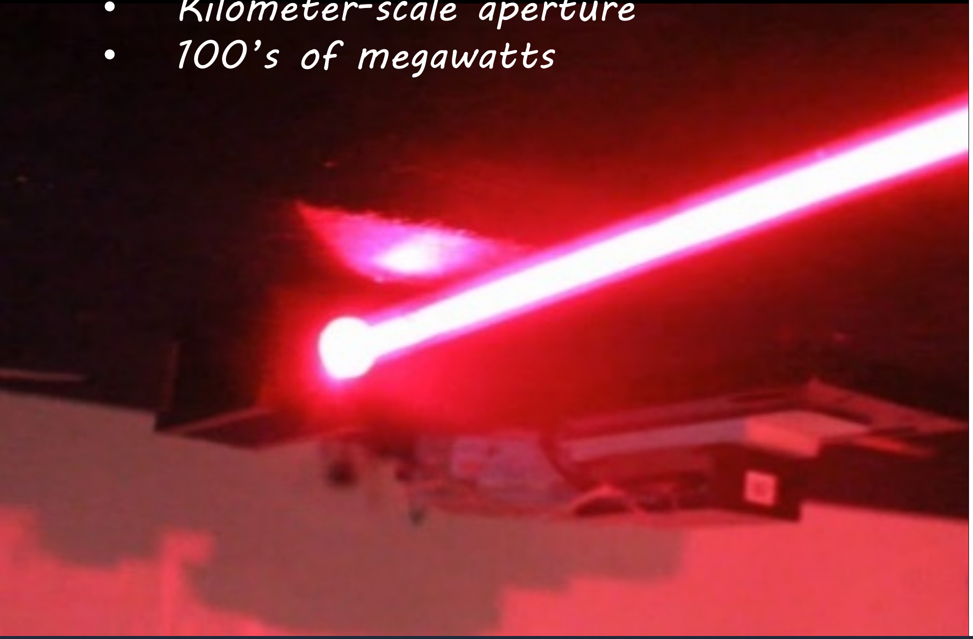
Pre-Decisional Mission Concept


Lithium-fueled ion engines
Array cells tuned to the laser frequency for efficiency > 50%
Laser Beam
Array output voltage of 6 kV
110-m diameter photovoltaic array with an areal density < 200 g/m²
Lithium-fueled ion engines
Artist's concept
Pre-Decisional Mission Concept

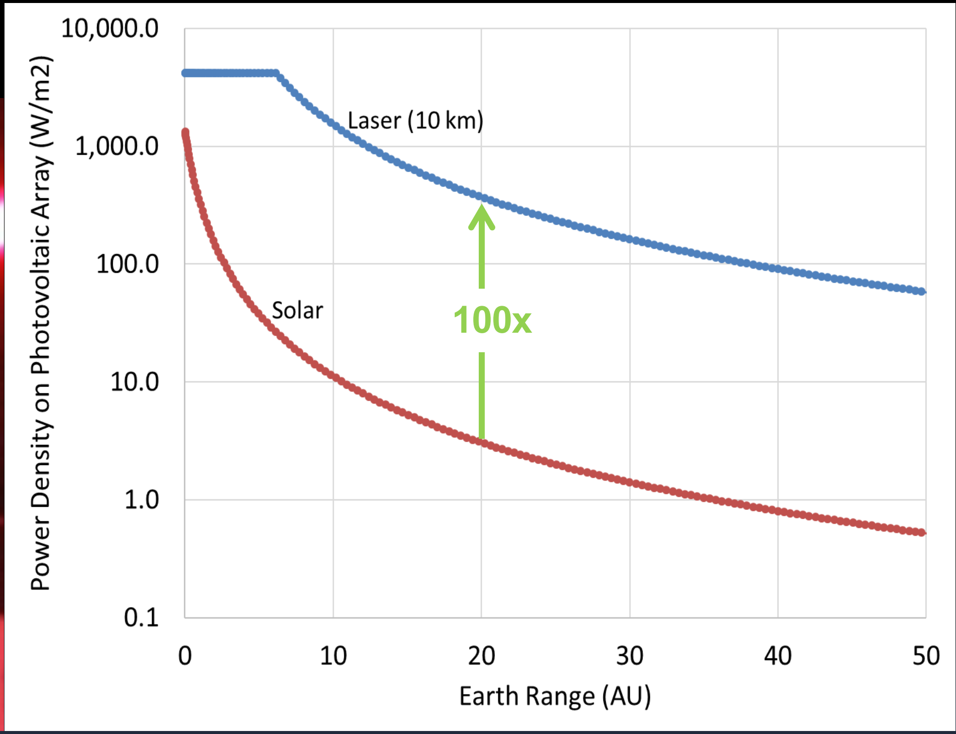
LASER

High-power, space-based laser

- Phased array
- Kilometer-scale aperture
- 100's of megawatts



Beam Power Across the Solar System



Artist's concept

Popular Mechanics

Humanity's Biggest Machines Will Be Built in Space

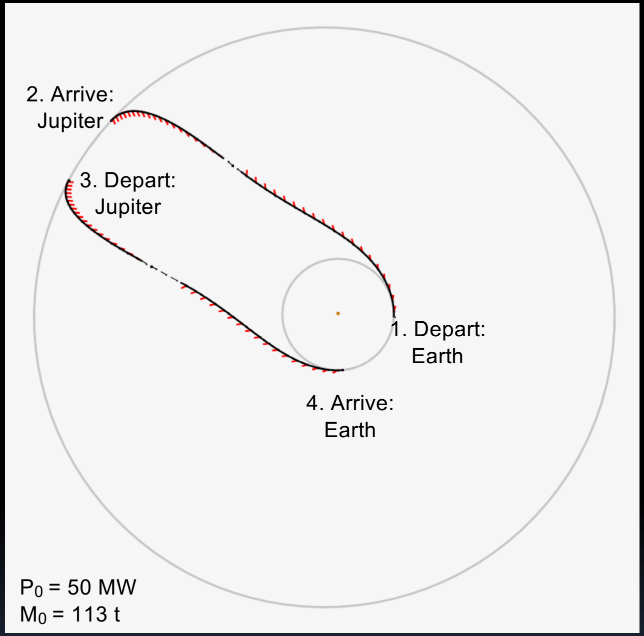
By Avery Thompson, Feb 16, 2018

“A mile-wide satellite might sound impossible, but that’s exactly where the space industry is headed.”

Human-scale Missions to Jupiter and Saturn

- Low α and high-power enables human-scale missions to Jupiter
- ~70,000 kg dry mass

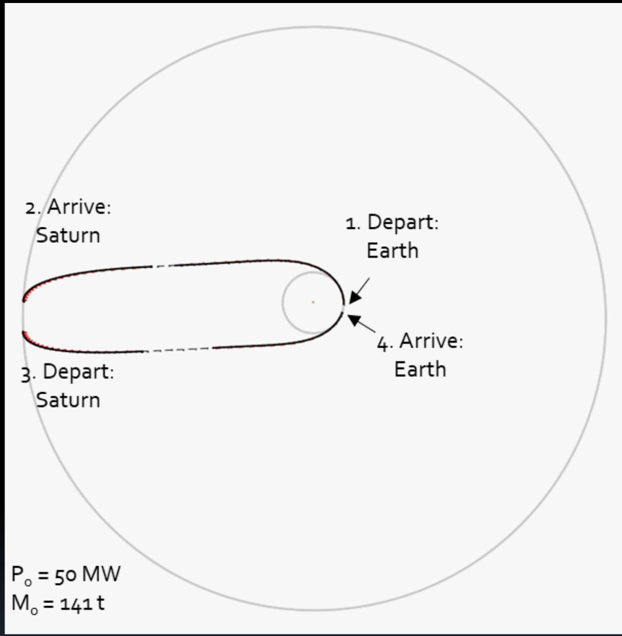
Jupiter



Roundtrip TOF: 2.8 Years
180 days at Jupiter

- 1.15-yr outbound
- 0.5-yr stay
- 1.15-yr return

Saturn



Roundtrip TOF: 4.0 Years
180 days at Saturn

- 1.75-yr outbound
- 0.5-yr stay
- 1.75-yr return

Jet Propulsion Laboratory
California Institute of Technology